Commanding Curiosity from the Couch: MSL Remote Operations, Challenges, and Path Ahead

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Abstract— **This paper describes how the Mars Science Laboratory (MSL) project prepared for and successfully began Curiosity rover Mars operations from their homes in response to the COVID-19 work-from-home orders. In a very short period, the team developed procedures and executed a remote operations readiness test in parallel with the team's support for nominal operations. Continuing regular rover operations with an entirely remote team had not previously been considered feasible due to a variety of factors. These included both the human factors, such as multiple concurrent person-to-person interactions of the uplink planning team, as well as technical factors, such as reliance on powerful workstations dedicated to graphically intensive software tools used for planning. The test was conducted on March 12, 2020, with both the downlink and uplink teams successfully simulating a near full planning day. The JPL administration announced the transition to mandatory telework on Monday, March 16. MSL stood down the uplink planning originally scheduled for the next day while downlink continued monitoring the rover. Full operations then resumed per schedule with nearly the entire operations team teleworking on Friday, March 20, during which the team planned rover activities for three Martian days (sols). These activities included the successful drilling of the "Edinburgh" rock target, a highly complex robotic arm contact science activity.**

As of October 1, 2020, the Mars Science Laboratory mission operations team has conducted 88 remote tactical uplink shifts for a total of 190 sols of planned rover activity, which accounts for more than 6% of the mission to date. In this period the rover has completed four drilling campaigns and driven over 1160 meters towards its next major science target – a sulfate bearing geologic unit at the foot of Mount Sharp. Success has not been without its challenges. Many of these have been addressed while others will remain in some form until the team can safely return to JPL, which in turn is the largest challenge for the future.

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Nomenclature

ADSL	Asymmetric Digital Subscriber Line
DRT	Dust Removal Tool
DROTT	Downlink Remote Operations Thread Test
DSN	Deep Space Network
ECAM	Engineering Camera
FCC	Federal Communications Commission
GDS	Ground Data System
GUI	Graphical User Interface
ISP	Internet Service Provider
JPL	NASA Jet Propulsion Laboratory
LTP	Long Term Planner
MAHLI	Mars Hand Lens Imager
MER	Mars Exploration Rovers
ML	Mission Lead
MSL	Mars Science Laboratory
MSLICE	Activity planning and commanding software
PC	Personal Computer
PDL	Payload Downlink Lead
PUL	Payload Uplink Lead
ROUTT	Remote Operations Uplink Thread Test
RP	Rover Planner
RSVP	Rover Sequencing and Visualization Program
RTG	Radioisotope Thermoelectric Generator
SAM	Sample Analysis at Mars
SSH	Secure Shell
SIE	Sequence Integration Engineer
SP	Science Planner
SuTL	Supratactical Lead
SOC	Science Operations Coordinator
SOWG	Science Operations Working Group
sol	Martian Day, ≈ 24.6 Earth Hours
TDL	Tactical Downlink Lead
TUL	Tactical Uplink Lead
UDP	User Datagram Protocol
VNC	Virtual Network Computing
VSTB	Vehicle System Testbed

1. INTRODUCTION

The Mars Science Laboratory (MSL) mission has been operating the Curiosity rover—exploring Gale crater and the base of Mount Sharp—continuously since early August of 2012. During this period (more than eight years as of this writing), the mission has gathered significant science data regarding the geologic history and habitability of early Mars. The MSL operations team has continuously refined and improved its operations processes during that period, while mitigating or correcting occasional spacecraft anomalies.

For the first seven and a half years of the surface mission, engineering operations team members were co-located at the Jet Propulsion Laboratory (JPL) in Pasadena, California. Science and instrument operations team members were virtually co-located with the engineering team, while operating from their home institutions. With the rapid spread of the COVID-19 pandemic in early 2020, both the MSL science and engineering teams faced a challenge unique in Curiosity's mission: to continue Mars exploration with a comparable rate of mission return, even as effectively all operations team members were required to abandon their workplaces in favor of physical isolation in their own homes. Initially, the MSL project investigated the feasibility of operating the Curiosity rover remotely as a potential short-term emergency measure. That potential was realized when JPL ordered personnel to transition to telework, with the early expectation that telework would be required for a number of weeks. Fully-remote operations[1] have now been ongoing for many months, and will likely continue for a total of a year or longer.

In this paper we describe the fundamental MSL operations design, the perceived road blocks to fully-remote operations, and the modifications to operations processes that were developed to respond to those road blocks. We then address the preparations and the testing that enabled the transition to fully-remote MSL operations. Finally, we consider the prospect of sustaining effective remote operations for the foreseeable future.

2. MSL OPERATIONS OVERVIEW AND STRUCTURE

The operations concept for MSL is driven by a number of constraints.

- Earth-Mars communications time delays: round-trip communications time is between 5 and 40 minutes, depending on the relative positions of the Earth and Mars. This communications time delay precludes real-time monitoring of spacecraft activity execution by ground-based operators.
- Limited communications opportunities: the rover can receive commands only when the Earth is visible in the Martian sky at the rover's landing site. Communications opportunities are further constrained by the availability of the over-subscribed Deep Space Network (DSN), which must service dozens of spacecraft across the solar system.
- Limited telemetry bandwidth: essentially all data available to the operations team is returned to earth (downlinked) via science orbiters at Mars, which together provide a relay capacity of ~500 Mbits per Martian day.

[1] In this paper "fully-remote operations" is used to refer to the period during which all MSL operations team members conducted operations from their homes instead of at JPL. "On-site operations" is used to refer to the period during which the MSL operations engineering team conducted operations from JPL while the majority of the science team members participated remotely from their respective institutions.

Unlike most deep space robotic missions, as a surface rover mission, MSL must be reactive and discovery-driven, such that the activities planned for the current sol (Martian day) are dependent on the results of the activities performed during the prior sol. For example, whether a specific rock target is worth sampling with the rover's drill will depend on the results of analyses performed by the rover's onboard instruments and on imagery captured by the rover's cameras. During rover traverses, the planned route depends upon the imagery captured at the end of the previously planned drive.

Strategic Planning Processes

The strategic level of operations incorporates planning on a scale of weeks to months. Among the strategic planning processes are long-term science plans, scheduling of tactical timelines, spacecraft trending, consumable resource tracking, and personnel scheduling. For example, the strategic route planning process defines and updates the Mount Sharp ascent route, which specifies a route on the scale of kilometers that meets the requirements of being traversable by the rover while reaching regions of scientific interest. This effort relies on orbital imagery and correlation of prior ground truth with that imagery.

The MSL strategic communication team negotiates with the DSN for antenna allocations to support command uplink opportunities. The team also works with Mars orbiter missions and other landed Mars missions for relay overflights to enable downlink of telemetry.

Supratactical Process

The supratactical process [1] maintains the overall rover plan for the next several sols, and in some cases for up to two weeks. With inputs from both the science and engineering teams, the Supratactical Lead (SuTL) updates the "look-ahead" plan that addresses sol-to-sol logical and resource dependencies. Some coordinated activities, such as sample drilling and subsequent analyses, are organized into multi-week campaigns. The rover's power source is a set of batteries charged by a radioisotope thermoelectric generator (RTG); the limited capacity of the RTG relative to the energy needed by rover subsystems and instruments requires the team to manage the state-of-charge of the batteries. If an energy-intensive activity is anticipated to be executed several sols in the future, the supratactical process will specify limits on energy usage for earlier sols and provide those limits as an input to the tactical process. The look-ahead plan is modified as necessary to ensure that the complexity of the activities in any single tactical planning cycle will be feasible for the tactical team to incorporate in a single work shift.

The primary deliverable from the supratactical to the tactical process is a skeleton activity plan that provides a broad outline of the sol(s) to be planned during the tactical process. The skeleton plan provides the overall structure of the sol, including the timing of orbiter relay overflights. The tactical process will evolve the skeleton plan into the detailed activity plan for the sol.

Tactical Process

The operational need to respond to the results of the latest rover activities led to the development of a daily "tactical" operations process, which generates the command load governing the Curiosity rover's activities for typically one to three sols.

The tactical process depends on the timely receipt of "decisional" data, or data that has been prioritized to inform the next tactical planning cycle. (Non-decisional data includes additional engineering data, imagery, and science results not immediately needed for operational decision-making.) Decisional data is usually relayed via a Mars orbiter late in the rover's afternoon, after the rover has completed all activities that will significantly impact its state and location. With the rover's activities synchronized with the Martian day, and a sol being ~40 minutes longer than an Earth day, the decisional data is received by the MSL operations team roughly 40 minutes later each day. With decisional data available at the start of the work shift, the key steps of the tactical process are:

1) Downlink Assessment
    a. Engineering downlink assessment. The engineering team performs an evaluation of rover health, state, and performance, including the success of the execution of the prior sol's activity plan.
    b. Science downlink assessment. Science operations team members determine instrument health and evaluate the success of instrument data collection.
2) Activity planning
    a. Science activity planning. Science theme groups define specific desired rover science activities and submit them for inclusion in the current sol's plan.
    b. Engineering activity planning. Engineering teams submit engineering related activities for inclusion.
    c. Rover motion activity planning. Rover motion activities may include traverse, multiple instrument placements, drilling, or sample delivery.
3) Activity plan refinement and validation: Activities are updated and reviewed to ensure that the desired activities are feasible within the rover's available resources (time, energy, available downlink data volume).
4) Activity plan approval.
5) Implementation of activities as command sequences.
6) Validation of sequences and the integrated command load.
7) Command load approval.
8) Uplink of command load via the ACE role through a DSN station.

Depending on the complexity of the rover's activities and the number of sols to be planned, the mature pre-pandemic duration of the tactical process was typically seven to nine hours. Early in the mission, the tactical process was exercised seven days a week. For reasons of sustainability and economy, the frequency of commanding has reduced over the years of the surface mission. MSL currently exercises the tactical cycle three or four days per week, depending on the current Mars-Earth time phasing.

JPL On-Site Operations

Prior to the move to fully-remote operations, MSL engineering operations were conducted at JPL's campus in Pasadena, CA. Two large rooms located in the JPL Space Flight Support building host MSL tactical and supratactical operations. The rooms include co-located high-performance computing workstations connected to the MSL Ground Data System (GDS), video projection systems, and telecom infrastructure. The layout of each room is intended to facilitate the frequent verbal and visual communication between team members that is necessary for the operations processes.

The Downlink Room, shown in Figure 1 (diagram) and Figure 2 (photo), is configured with stations dedicated to each of the spacecraft's individual engineering subsystems, such as Power, Mobility, and Thermal. During tactical downlink operations, engineers representing each rover subsystem perform analyses within their particular domain. The downlink assessment effort is led by a central role, the Tactical Downlink Lead (TDL). All subsystem workstations are oriented facing the TDL and a set of video projection screens.

The TDL conducts each downlink shift by utilizing the video projection system in the Downlink Room to display for the team information relevant to the downlink assessment (e.g., the time range of spacecraft data to assess, context about the activities that were expected to execute onboard the rover during that period). Although all personnel participating in

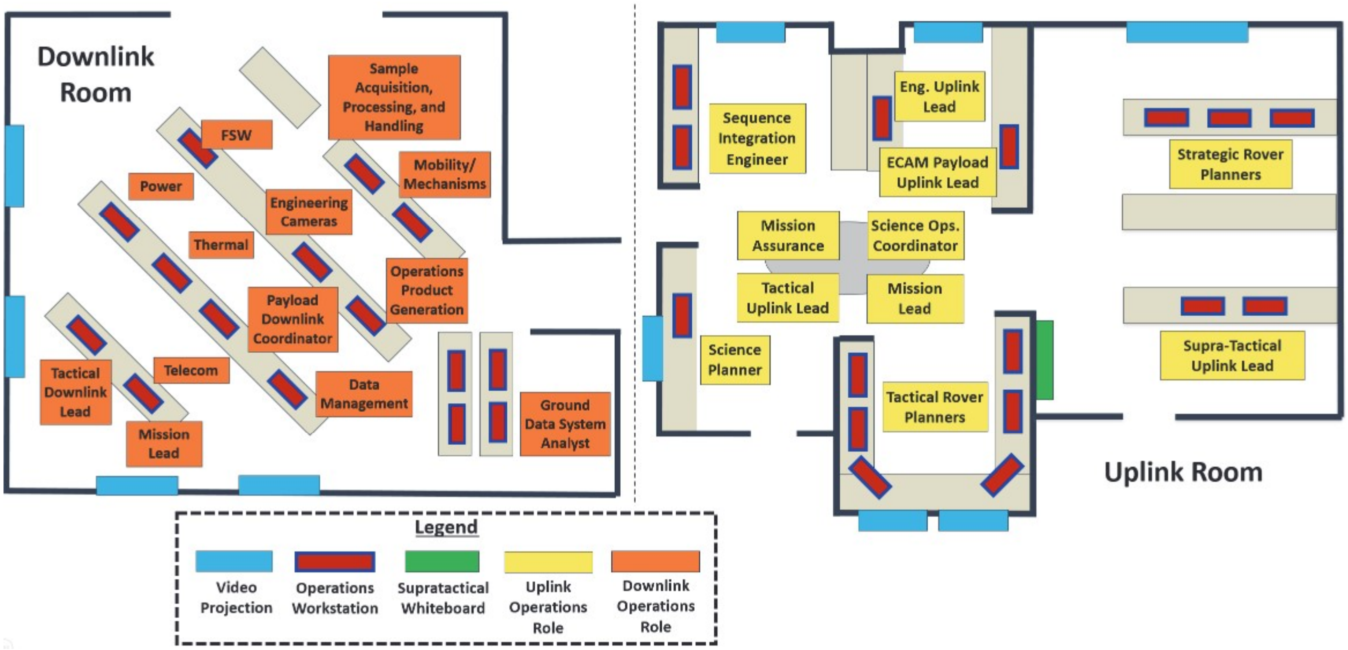

Figure 1. The MSL Downlink Room and Uplink Room at JPL. Tactical and supratactical on-site operations are conducted in these rooms.

the downlink shift are located together in the Downlink Room, voice communication between team members is done using headsets and a networked audio system due to the size of the space. Under on-site operations, tactical downlink operations do not use any type of remote web conferencing.

The Uplink Room, also shown in Figure 1 (diagram) and Figure 2 (photo), contains stations for each of the individual engineering uplink roles. The Uplink Room is purposefully arranged to allow easy in-person communication between certain roles and multiple views of the room's video projection systems. The Tactical Uplink Lead (TUL), Mission Lead (ML), Science Operations Coordinator (SOC) and the Science Operations Working Group (SOWG) chair (when present at JPL) work on laptops at a central table. This placement allows them to both visually monitor and acoustically survey the room to participate in the various on-going discussions around them.

The TUL is the manager of the uplink process. The TUL oversees not just the technical side of the process, but also manages the team and planning timeline. A key aspect of this role is to detect signs of stress or problems within the team and to provide support, including assistance with problem solving and interfaces. More than other roles, the TUL traditionally has relied not just on being able to participate in and be aware of discussions within the room, but also on visual cues, such as body language and transitions in and out of the room. In this way, the TUL can be proactive without being overly intrusive to the tactical process and can more

Figure 2. Photos of MSL operations team members working inside the MSL Downlink Room (left) and Uplink Room (right).

easily judge when questions or interruptions would be more or less disruptive.

The Tactical Rover Planner (RP) role uniquely requires multiple individuals staffed at once due to the role's complexity. The group of tactical RPs sits in a cluster so that individuals can easily turn around to view others' workstation screens and have detailed discussions without disturbing other roles. The Rover Planner process relies on the collective viewing and discussion of rover telemetry, stereoscopic imaging, and 3D renderings of rover simulations and terrain. The majority of the process is conducted using Robot Sequencing and Visualization Program (RSVP) [2]. Content from RSVP is viewed on the workstations' stereoscopic 3D monitors that work with synchronized, shuttered 3D glasses. Strategic RPs, who support the supratactical process, work out of an adjacent area of the Uplink Room, allowing the two types of RPs to quickly access one another.

The other engineering uplink roles are located around the perimeter of the room. Throughout most of the planning day, the Science Planner (SP) typically shares their workstation screen on the room's projection screens and on the tactical web conference room so that all team members, local and remote, can follow along. The shared content is from MSLICE [3], an activity planning tool used to schedule, coordinate, and visualize all the planned spacecraft activities. Since the tactical timeline is driven by the readiness of the activity plan, the SP and TUL have frequent discussions throughout the planning day to discuss the state of the activity plan and various activity constraints. SP must also work closely with the RPs to accurately model the rover planning activities sequenced by RPs in RSVP. Other science and engineering activity fragments are typically delivered directly to the SP through MSLICE, and require little modification. When the plan is finalized, the SP hands off to the Sequence Integration Engineer (SIE). The SIE implements the intent of the plan in the top-level sequences, integrates command sequences delivered by all of the teams, and models them to ensure correct behavior. The SIE then bundles the sequences for delivery to the ACE.

The last step of an operations day is to deliver the command bundle to the ACE to transmit to Curiosity via a DSN station. The ACEs use a specific workstation and web interface that connects to the DSN station antennas in Goldstone California, Madrid Spain and Canberra Australia. The ACE is behind an additional firewall internal to JPL and uses a multi-mission toolset.

Existing Remote Operations Infrastructure and Capabilities

MSL tactical and supratactical operations teams are also made up of many remote team members who participate in the operations processes from other institutions and, occasionally, from home offices. As will be discussed later, the infrastructure that enables this remote collaboration was used as a basis for moving to fully-remote operations. Previously, most remote collaborators were science operations team members, including Payload Downlink and Uplink Leads (PDLs and PULs), SOWG Chair, Long-Term Planner (LTP), Geology (GEO) and Environmental (ENV) Science Theme Leads (STLs) and the GeoKOP (the role that builds GEO's activity fragment). These collaborators connect to the MSL GDS through JPL VPN connections from their remote locations. A block diagram illustrating the network layout of JPL local and remote team members during on-site operations is shown in Figure 3.

During on-site operations, various MSL operations roles use remote desktop Virtual Network Computing (VNC) configured in Virtual Mode as a way to access MSL workstations. During on-site tactical shifts some TULs use VNC to access MSLICE and run scripts that could not be run on their laptops. Science Planner and Sequence Integration Engineer roles use VNC connections to facilitate training and testing from the user's desk in lieu of going to a computer lab. VNC also allows users to have a dedicated remote interface that continues to run when unattended or disconnected. In downlink, some roles leave telemetry analysis tools running in VNC sessions to capture information as it arrives from the DSN. This broad familiarity with VNC provided a starting point for the operations team to transition to use for fully-remote operations.

A significant component of the MSL operations collaboration is the MSL GDS and the interactive software tools that interface to it. Of these interactive tools, the MSL Reports web application, is the primary communication hub. MSL Reports includes dedicated pages for uplink and downlink roles, science instruments, and spacecraft engineering subsystems. A set of pages is provided for each sol of the mission. Strategic activity outlines and staffing schedules are also included in MSL Reports. An essential part of the tactical and supratactical operations processes is the automated and manual posting of key data to MSL Reports and review of that data by the various team members.

Communication with remote team members is conducted through several channels. Enterprise web conferencing rooms are used to host the routine virtual meetings conducted during tactical and supratactical operations. Within these virtual rooms, audio conference and screen sharing are the primary means of communication. Team members, remote and at JPL, join the rooms at the beginning of each tactical shift and stay connected to the same room throughout the tactical day. In most cases, team members would only need to participate in one web conferencing room at a time. A notable exception is the Science Operations Coordinator (SOC), who frequently participates in multiple rooms simultaneously during on-site operations due to their cross-cutting role.

In addition to web conferencing, MSL Operations relies on text chat rooms hosted on the MSL GDS. Chat rooms are dedicated to specific collaboration areas or teams, such as RPs, science theme groups, and individual science instruments. The rover planning chat room in particular is the

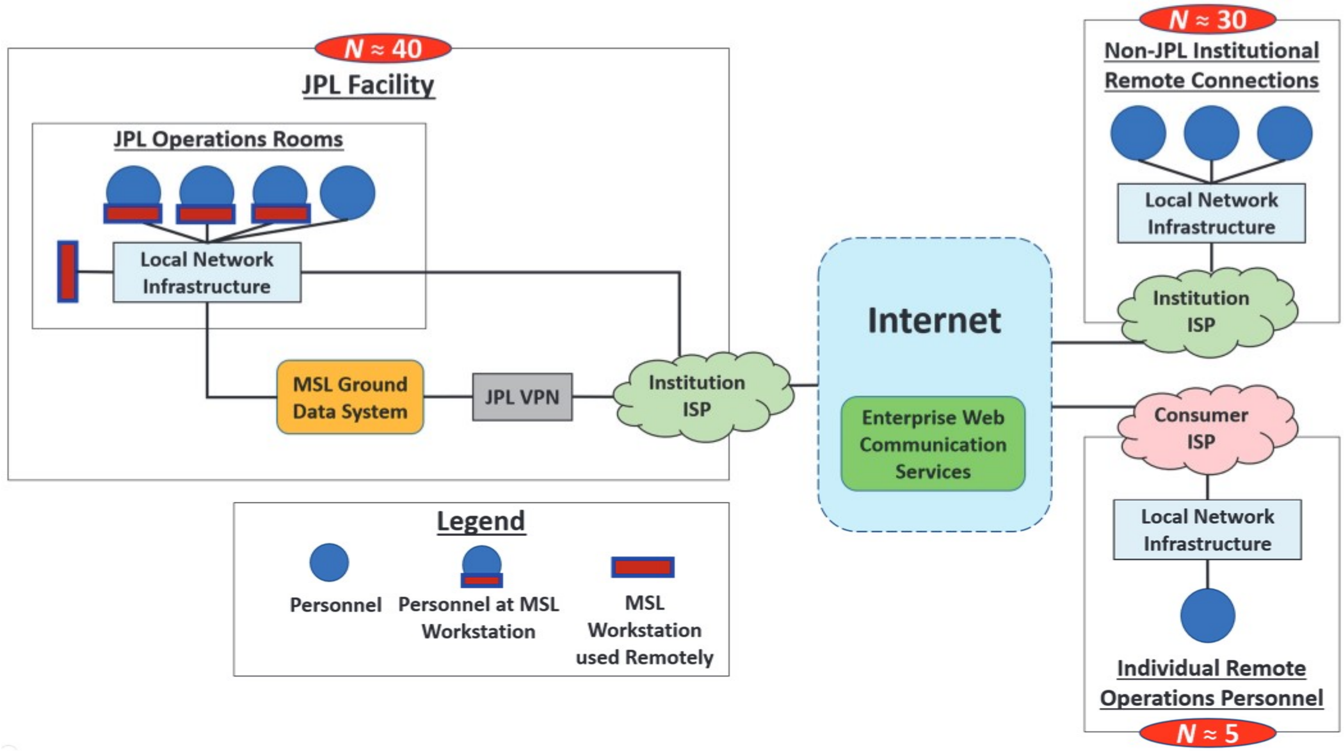

Figure 3. A block diagram illustrating the network structure of JPL local and remote team members during on-site operations. The red bubbles indicate the average number of participants connecting from the respective locations.

primary channel used to discuss robotic arm contact science and mobility activities between the RPs and Science PULs.

For MSL downlink operations, typical responsibilities and interactions are relatively well-suited to remote participation. For the most part, analyses within each spacecraft subsystem are performed independently of one another and all subsystem teams have their own workstations that host remote access to rover telemetry. Although direct communication among subsystem engineers can be beneficial when assessing rover health and performance (especially in the event of anomalies), most of the communication during downlink operations is handled by the TDL, who is responsible for receiving inputs from each subsystem to determine the overall state of the Curiosity rover.

Prior to the start of fully-remote operations, MSL management had already approved several subsystem roles to support downlink shifts remotely. This allowance had previously been used by personnel with existing flex work and telecommuting agreements, as well as team members with conflicting responsibilities on the project (for example, when an individual was needed for testbed operations at the same time as a downlink shift). More recently, additional subsystem teams had also been working to add automation in their downlink processes to reduce assessment times and eventually enable entirely remote support. These factors greatly aided in the team's readiness to perform fully-remote downlink assessments.

3. Challenges to Fully-Remote Operations

The COVID-19 pandemic and prospect of mandated remote-work scenarios led the MSL operations team to consider the feasibility of fully-remote operations for the first time in late February, 2020. While MSL had used flex remote work for tactical downlink operations since fall 2019, several key aspects of operations imposed serious challenges to realizing fully-remote operations in response to the COVID-19 pandemic.

Software Tool Access and Performance

As discussed in Section 2, MSL operations relies on a suite of interactive software tools that interface to the MSL GDS hosted at JPL. Those tools can be broken up into two main categories: highly interactive tools with graphic user interfaces and command line accessible tools. Fully-remote operations require that both classes of tools remain accessible with highly reliable performance.

Fortunately, standard remote terminal access services, such as SSH [4], and the existing remote operations infrastructure for external collaborators provided a ready means to run many tools remotely. Using a JPL VPN connection, many

GUI tools were either previously built to run on personal machines connected to the MSL GDS, or could be launched with high reliability through SSH X forwarding (a method of running GUI applications over the SSH protocol) from an MSL workstation at JPL. Command line tools have long been used remotely over SSH either by MSL users at JPL and remotely over a JPL VPN connection.

MSLICE [3] is a highly interactive graphical tool used by many members of the uplink operations team. A large subset of MSLICE users have always run it remotely on Windows and Mac OS computers from other institutions. Science team members use MSLICE remotely to create and deliver activity plan fragments which are integrated into the plan to model time, power, and data. Although MSLICE was developed to be used by a wide variety of users on both laptops and workstations, in the operational environment, the SP and SIE use cases have very specific needs in order to interface with the MSL GDS. The SP and SIE use MSLICE in a Linux workstation environment that is integrated with both the downlink processing for initial conditions and the delivery of sequence bundles to the DSN for radiation to the rover. This requires the remote SP and SIE to use MSLICE running on an MSL workstation at JPL and interact with the software directly at a workstation or through a remote desktop connection. Furthermore, the centrality of these roles in commanding the rover requires that a backup SP or SIE is able to take over in the event that the scheduled operator loses internet connection. For fully-remote operations, a remote desktop solution would need to allow other team members to take over without interruption, if needed.

RSVP, the GUI simulation and visualization tool used by the RPs, is a notable exception in the MSL software tool suite in that it was intentionally built to run only on specific high-performance MSL Linux workstations. Due to the tool's reliance on local 3D rendering on a graphics card, SSH X forwarding was not feasible.

In all cases of remote tool use, a stable and high-bandwidth connection to the MSL GDS through the general JPL VPN is required. Since the connections are made on a per-user basis for remote personnel, numerous points of failure exist between a user's machine and the MSL GDS. Furthermore, conditions external to the MSL operations team impact VPN performance, such as JPL Network down times or a high influx of VPN users. Software tools used through SSH X forwarding and those relying on a connection to the MSL GDS through the JPL VPN are susceptible to performance drops or loss of connection, which result in severe impacts to operations workflows or loss of work products.

Remote desktop connections to MSL workstations at JPL through VNC offer a robust solution to these issues. VNC severs continue to run, even in the event of household internet service interruption or a JPL VPN outage, allowing the operator to quickly reestablish the connection, switch to a backup connection (like a 4G hotspot), or to smoothly hand off to a replacement operator without any loss of work. Details of the VNC configuration specific to MSL operations needs and implementation are discussed in Section 4.

Communication Channels

Fully-remote operations would need to rely on alternative means of holding the parallel in-person discussions, collaborative analysis, reviews, and content sharing that take place in the MSL Uplink and Downlink Rooms. Historically, MSL operations has taken advantage of the physical layout of operations rooms to enable parallel in-person interactions with limited disruption. As mentioned in Section 2, certain roles will in fact "monitor the pulse" of the operations room by visually observing and listening into concurrent discussions happening around them. This helps to avoid repetition of certain reporting and can be used to pre-emptively identify issues impacting the tactical timeline.

Replicating the benefits of in-person interactions using the MSL existing web conference and chat room infrastructure would prove to be challenging. Parallel verbal discussions and screen sharing are not possible in a single web conference room. The parallelism issue can be partially addressed by expanding the number of web conference rooms to provide dedicated spaces for specific collaboration areas or teams. However, certain team members would need to monitor and participate in multiple rooms at once, a logistically complicated and stressful imposition. This can lead to missed information, when attention is elsewhere, and to delays. Additionally, inherent non-verbal communication must be replaced with explicit and sometimes intrusive verbal communications and check-ins, which can be disruptive to the process, or with chat communications that can be slow to be received.

Technical issues can arise when using enterprise web conferencing services and personal audio equipment. Services can have outages, audio quality can drop, and equipment can be misconfigured or fail. These types of issues are often intermittent and inconsistent across team members. Technical issues are compounded by the mental strain associated with the extended use of web conference. As is now all too familiar to many in the time of COVID-19, "Zoom fatigue" [5] is a phenomenon many experienced after hours of back-to-back virtual meetings. Since screen content sharing is nearly constant during MSL operations, personal video has never been used during operations. However, team members have found it very difficult at times to mentally track conversations with multiple individuals without the benefit of in-person visual cues over a tactical operations shift of at least six and up to ten hours in duration. Taken together, these challenges associated with replacing in-person communication with web conferences potentially introduce communication errors and timeline delays. These impacts would need to be addressed through modified MSL operations processes.

Individual Environment, Hardware, and Local Factors

On-site operations at JPL benefits from a high amount of

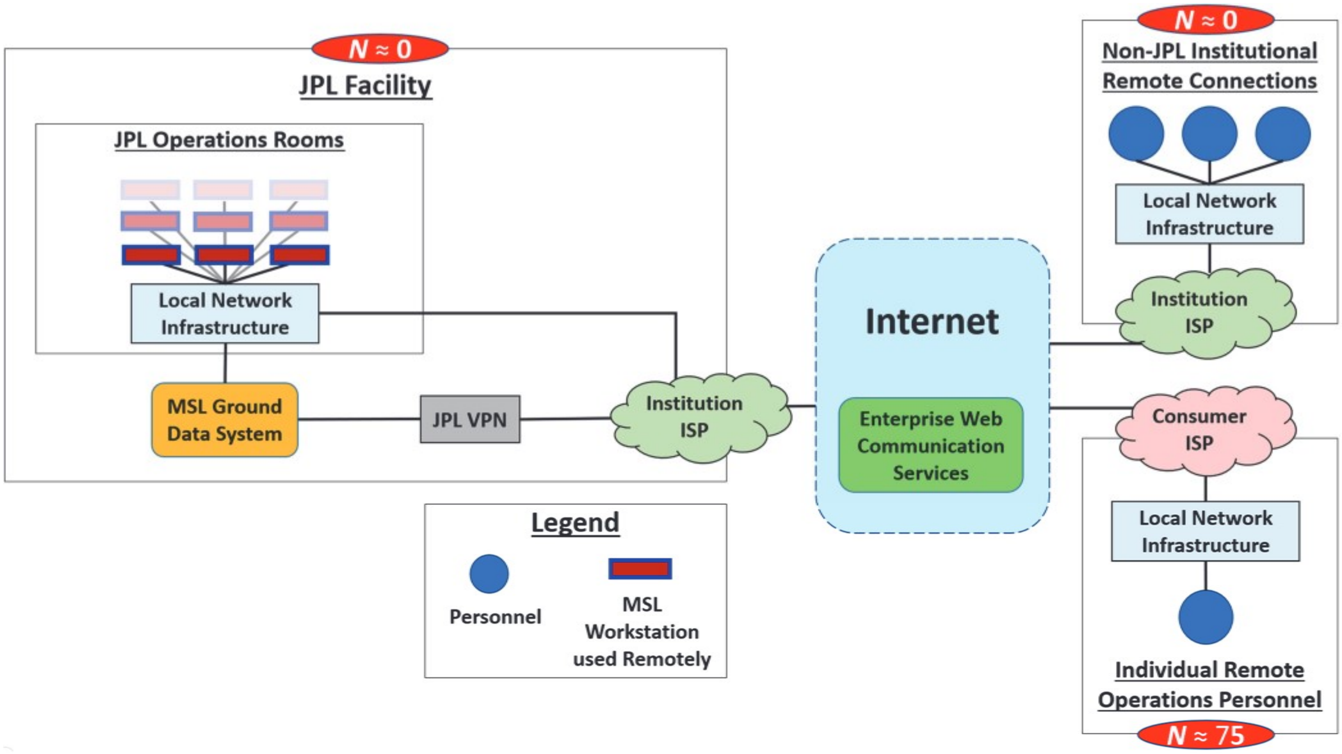

Figure 4. A block diagram illustrating the network structure of JPL local and remote team members during fully-remote operations. The red bubbles indicate the average number of participants connecting from the respective locations. For fully-remote operations, all participants are typically working from their homes through consumer ISPs.

control over the operations environment, hardware setups, and local factors. Outside disruptions are virtually non-existent at JPL, besides the occasional evacuation drill. Computing, networking, and teleconferencing equipment are all sourced and managed by the MSL operations infrastructure team. JPL's network reliability is very high relative to consumer Internet Service Providers (ISPs), and networking hardware and the building are on an uninterrupted power supply. A move to fully-remote operations introduces a high amount of variability in these areas, as most team members would end up working from their own homes.

To address these concerns, guidelines for suitable home office environments would need to be generated. Computer peripheral and teleconferencing hardware would need to be distributed and replenished as needed. At-home network connections would need to be qualified and processes put in place to respond to individuals losing connection to JPL VPN or enterprise communication services. These efforts would still leave team members open to local disruptions, such as children, pets, or home maintenance.

4. Detailed Changes to Support Fully-Remote Operations

The challenges outlined in Section 3 were addressed by making a number of changes to MSL operations processes and through the introduction of new tools. This section describes their details and implementation.

Structure of Remote Connections

Fully-remote operations introduces a modified structure of the various connections to the MSL GDS. This structure is provided in Figure 4 and can be compared to the on-site operations structure shown in Figure 3. The fully-remote structure removes all personnel working on-site at MSL workstations at JPL. The structure also alters the number of remote connections to the MSL GDS over the JPL VPN. The new structure is supported by occasional on-site technical support for critical equipment maintenance or robotic testbed work for anomaly response. These changes significantly increase the number of functional unique remote connections by an order of magnitude on any given operations planning day. Each of these remote connections now relies on functioning JPL VPN, consumer ISP reliability, and local networking hardware. Historically, some remote connections for instrument teams were hosted from collaborator institution operations rooms, such as at universities. In these cases, the ISP and networking hardware would be enterprise-grade with a much higher reliability and up-time compared to consumer solutions. Like JPL, most remote collaborators on the MSL science operations team were also subjected to work-from-home orders, eliminating the use of remote institutional operations rooms.

Each functioning remote connection to the MSL GDS is a single point of failure for the respective individual's ability to participate in an operations shift. Through the introduction of many more single failure points, the overall robustness of the structure is significantly decreased. Anecdotally, this reduced robustness takes the form of reduced operations efficiency and occasional descoping of activities due to home internet outages, or other disruptions, and JPL VPN server faults.

The drop in remote connection robustness needed to be mitigated to reduce impact on operations. A summary of team testing of their individual connections is provided in Section 5. Other mitigation efforts involved use of alternative internet connections through mobile 4G hotspots, an extended use of VNC, an increase in number of roll call check-ins with team members during operations shifts, and redundancy in staffing.

Remote Use of Software Tools

The relatively obvious solution to the remote use of MSL software tools was relocating MSL workstations to team members' premises. However, this solution was precluded by physical security, equipment availability, and GDS configuration considerations. Prior to selecting remote desktop VNC, a number of options were reviewed to supplement the existing remote operations infrastructure discussed in Section 2. The selected solutions needed to support a variety of computing operating systems and work with as low as a 25mbps connection. A minimal configuration on each client's computer was required to ensure that users could access all software tools with ease. The solution would need to make use of 3D hardware acceleration to run the RSVP software used by RPs. In the case of RSVP, one option considered was using Docker, a virtualization system that enables the deployment of applications within virtualized containers [6], to package RSVP entirely and distribute it to the operations team. However, the operations team determined that the Docker approach would require prohibitively large development to robustly interface to the MSL GDS and therefore was not pursued. In addition, there was concern that users' personal work computers, typically laptops, would not have the resources required to run RSVP through Docker.

Building on the existing on-site use of remote desktop software, VNC was tested and initially determined to work effectively across a wide variety of MSL tactical and supratactical use cases, despite increased latency for users. The MSL operations infrastructure team configured VNC Server Mode on a subset MSL workstation at JPL to match the machines' expected use by remote team members. VNC Virtual Mode is used on most machines, allowing those machines to host multiple remote users not requiring graphically intensive applications. VNC Service Mode is used on machines running RSVP. This mode allows for full use of workstation 3D hardware acceleration across two virtual monitors (mirroring the two monitors connected to the on-site workstations at JPL). RSVP users would need two physical monitors to mimic the on-site environment. One downside to VNC Service Mode is that only one user can login to a machine at a time, requiring coordination amongst the RP team members. Later, a web dashboard was created to allow users to track which machines are available or in-use. Efforts were made to improve VNC performance by using User Datagram Protocol as well as sharing 3D hardware acceleration resources across multiple VNC desktops on a single machine. Neither effort showed significant benefit.

As discussed in Section 3, a benefit of the VNC solution has been the ability to fully recover a user's work in the event of a lost connection. During such events, users are always able to return to the same session in the same state as it was left or have another user seamlessly take over. For roles conducting such critical and time-intensive work as the SP, SIE, and RPs, this behavior has become crucial to their ability to weather all kinds of unexpected remote operations incidences with little impact to tactical timelines.

A limitation of the VNC solution for RSVP use was the inability to render rover and terrain visualization in 3D in the same manner as on-site use. As discussed in Section 2, MSL workstations for RSVP have stereoscopic 3D monitors that work with shuttered 3D glasses. This type of rendering does not work over VNC, and instead RPs must rely on anaglyph stereo using red/cyan 3D glasses. This method provides less visual acuity when assessing the Martian environment in 3D; however, it was deemed adequate for RPs going forward.

Expansion of Communication Channels

Uplink—As discussed in Section 2, the use of web conference rooms serves as the primary replacement for the on-site interactions that occurred in the Uplink Room during operations. Additional web conference rooms were added to provide dedicated virtual spaces for specific collaboration areas or teams. The number of MSL-hosted chat rooms was also expanded. Lastly, the operations team mandated the use of an enterprise text chat service that was accessible on mobile devices and desktop systems without the use of JPL VPN. Table 1 illustrates these changes relative to on-site operations.

The reliance on web conference rooms has had a large impact on the MSL tactical uplink and supratactical communication procedures. Additional virtual role calls were introduced to ensure team members are not experiencing connection issues. Intermittent web conference service outages also had to be addressed. In most cases outages only impact a single individual or subset of individuals. This issue, along with occasional JPL VPN outages, promoted the use of the supplemental enterprise text chat service that operated independent of the JPL network. This chat service is used to reach individuals for status updates when other channels and connections fail.

During on-site operations, the RP and SP roles would share

Table 1. Summary of communication channel for fully-remote ops. Addition of channels is shown in orange.

Communication Channels	Operations Groups: Tactical Downlink	Tactical Engineering Uplink	Tactical Rover Planner	Tactical Science Uplink	Science Operations Coordinator	Supra-Tactical
Remote						
Enterprise Web Conference Rooms	1	1	2	1	4	1
MSL Hosted Chat Rooms	1	6	3	7	15	4
Enterprise Chat	1	1	1	1	1	1
On-Site						
Enterprise Web Conference Rooms	0	1	1	1	2	1
MSL Hosted Chat Rooms	1	5	3	7	13	3
Enterprise Chat	0	0	0	0	0	0

Legend: Increased under fully-remote

their screens on the Uplink Room's video projection systems to enable in-context discussion and review during tactical meetings. This same screen sharing is now done using the web conference service.

Remote tactical and supratactical operations requires RPs and SOC to stay dialed in and contributing to multiple web conference rooms at the same time. RPs use a dedicated web conference room, while also participating in the primary tactical uplink web conference room. While the web conference service allows simultaneous connection to multiple rooms in different application windows, simultaneously managing and using the audio connections to those rooms is non-trivial. In the case of RPs, team members use two single-ear microphoned headsets, with one headset connected to a computer running one web conference room and another connected to a phone dialed into another web conference room. This arrangement allows listening to both rooms at once, while being able to individually adjust volume or microphone mute state. Some RPs have recently started using desktop applications that allow users to create and manage multiple virtual audio streams that can then be directed to either channel of a single stereo headset. These users have found this approach easier to manage than the simultaneous desktop and phone audio connections.

SOCs actively participate in up to three web conference rooms at once, necessitating an alternative approach. Instead of launching multiple web conference application windows and audio streams on a single personal computer (PC), SOCs use multiple computing devices (typically two or more PCs and a tablet device). A web conference room is connected to on each device and individual device volume and microphone mute state is adjusted as needed. With this setup, single-ear audio headsets can be used by a SOC if desired, while the other audio channels are broadcasted from the other devices' speakers.

Downlink—A remote operations procedure for MSL downlink subsystems had previously been developed to allow select roles to connect to perform downlink operations via phone. Because of the limited number of remote participants in downlink shifts, audio-only teleconferencing had been sufficient for typical interactions. However, fully-remote downlink operations presented new challenges. A typical downlink shift begins with the TDL providing a briefing to all of the subsystem engineers on the context of the spacecraft activities being assessed. During on-site operations, the TDL simply displays that information using projectors in the operations area. Called-in users could always follow along by opening corresponding pages on MSL Reports. A web conference screen sharing capability had never been implemented for remote participants. Also, the existing method of patching phone connections into the networked audio system that is typically used for in-person assessment shifts proved inadequate for the full downlink team (which, at a minimum, consists of 11 participants). Consequently, a new method of web conferencing was needed to enable fully-remote downlink operations. The web conferencing system used for MSL uplink operations served as a model and ultimately provided a satisfactory solution for downlink.

Virtual Supratactical Whiteboard

MSL's supratactical process facilitates more optimal planning of rover activities during multi-sol campaigns by coordinating science and engineering priorities and constraints prior to the start of the tactical process [1]. One of the primary supratactical tools used for mapping out priorities and trade space were physical whiteboards located in operations rooms at JPL. Potential rover activities for the next two to seven sols were laid out there, providing a working template for the sol path. In order to replicate this functionality, the team designed and tested a virtual version of the whiteboard using an online collaborative spreadsheet. The collaborative and virtual nature of these whiteboards has been highly effective and will likely remain in use after the team safely transitions back to on-site operations at JPL.

RP Staffing and Plan Content Adjustments

MSL operations uses an activity scoring process and supratactical guidelines to manage the complexity of RP activities (mobility and robotic arm) that are brought to a tactical plan. The types and number of activities brought into a supratactical plan are limited based on what can typically be achieved with the tactical staffing levels in a planning day. The tactical team may choose to add or delete activities depending on the context of the tactical planning day and the certification levels of the staffed individuals.

During the early phases of fully-remote operations, the operations team observed limitations on effective collaboration through the RP web conference room when sequencing a large number of RP activities in a single planning cycle. The parallel conversations with RPs that occur in the Uplink Room could not be replicated on a single web conference dedicated to RPs. The team considered introducing a second RP web conference room, but the arrangement would sequester the tactical RPs from one another, while adding an yet another channel for other team members to manage.

These issues were addressed by reducing the maximum allowable plan complexity coming from supratactical and adding a dedicated communication RP to monitor all tactical communication channels. The types and number of activities allowed with the new remote operations RP staffing is provided in Table 2. Changes from on-site operations include reducing the maximum number of robotic arm contact science targets. The tactical team can still adjust the plan content based on priorities and staffing on the day.

Table 2. Summary of changes in supratactical RP robotic arm activities for fully-remote operations.

Plan Activities	Type of Robotic Arm Targets	On-Site	Fully-Remote
Arm Only	Generic Contact Science	3 →	2
Arm Only	Dust Removal Tool	2 →	1
Arm and Drive	Generic Contact Science	2 →	1
Arm and Drive	Dust Removal Tool	1 →	1

Fortunately, the changes to allowable supratactical complexity have not had a significant impact on the highest priority rover planning activities during fully-remote operations. As is discussed in Section 6, during the last six and half months of remote operations, the science team has prioritized rapid traverse to targeted geologic regions and the execution of drill campaigns. Certain tactical planning days have also been able to take advantage of the additional communication RP resource to plan activities beyond what was brought in from supratactical.

5. PREPARATION AND TESTING FOR REMOTE OPERATIONS

Timeline of Development and Testing

The MSL operations team developed and executed a transition to fully-remote operations over the course of 19 days. The timeline of events that led to the first fully-remote operations shift is illustrated in Figure 5.

Planning for fully-remote operations started in earnest at an MSL senior staff meeting on March 2, 2020. The intent was to be prepared for potential telework mandates due to pandemic conditions that called for changes in how the team operated while ensuring the safety of both the team and the spacecraft. An important goal was to minimize any loss to the mission's science during the pandemic period. Whatever remote operations capability was feasible, it required testing. In order to validate new remote procedures and tool use, MSL planned thread tests that would follow a complete operations cycle: tactical downlink assessment and tactical uplink command generation. A target date was set only ten days away on March 12, 2020, since it was already scheduled as a non-planning day.

In a couple of days, the team had assessed what impacts teleworking could have on Curiosity commanding content and each operations role's capabilities and resilience to potential absences caused by the illness itself. Many of the roles had exposure or access to the on-site remote operations infrastructure and could immediately start assessing its suitability for their roles in a fully-remote paradigm. The RP role was identified as the most challenging to adapt to fully-remote operations, and the RP team leads quickly identified the RSVP performance and communications needs with some potential solutions. A few options were investigated by the RP team, as discussed in Section 4, while the rest of the operations team started testing from home and updating procedures. Note that during fully-remote operations planning, the MSL operations team also continued supporting the daily tactical operations planning cadence in parallel.

On March 10, 2020, while teams were planning the details of the eventual thread tests, JPL announced that the rest of the facility would perform a lab-wide telework exercise on the same day as MSL, March 12, 2020. The MSL thread tests would now get the benefit of a more realistic remote infrastructure load, with a large portion of the JPL population making use of the JPL VPN and web conferencing services. The VNC Service Mode proved viable for the RSVP needs and was deployed to the test machines. New chat rooms and test web conference rooms were created, test procedures were completed, and the operations venue data was backed up. March 12 ended with fully successful execution of both the Downlink Remote Operations Thread Test (DROTT) and the Remote Operations Uplink Thread Test (ROUTT).

On March 16, 2020, JPL declared mandatory telework to start

Sun 3/1	Mon – 3/2	Tue – 3/3	Wed – 3/4	Thu – 3/5	Fri – 3/6	Sat 3/7
	Planning starts with target date of 3/12 for testing.		Assess remote impacts and staffing resilience. Start assessing remote software tool options.	Start developing thread test concepts leveraging on previous GDS update.	Team members begin testing from home and developing procedures.	
Sun 3/8	**Mon – 3/9**	**Tue – 3/10**	**Wed – 3/11**	**Thu – 3/12**	**Fri – 3/13**	**Sat 3/14**
	Schedule Thread Tests for 3/12	Hold Thread Test planning sessions. VNC service mode evaluation.	Deploy VNC Service Mode to test machines . Create new chat rooms and test web conference lines.	JPL Telework Exercise. Successful hold DROTT and ROUTT. Order additional equipment.	Inventory spare monitors, keyboards, mice, cables.	
Sun 3/15	**Mon – 3/16**	**Tue – 3/17**	**Wed – 3/18**	**Thu – 3/19**	**Fri – 3/20**	**Sat 3/21**
	Assess readiness for remote ops: Downlink: Go Uplink: by 3/18. Distribute newly arrived and spare MSL equipment to departing team.	JPL starts mandatory telework. Downlink supports remotely. Uplink stands down to incorporate lessons from ROUTT.	Update procedures and train team members. Setup permanent new chat rooms. Team continues testing from home.	Create and debug new ops web conference rooms. Update ops machines with VNC Service Mode. Remove ROUTT data from ops venue.	Successful first MSL fully-remote ops shift – Edinburgh Full Drill.	

Legend

Planning Day | Non-Planning Day

Figure 5. High level schedule of the MSL operations team's development and execution of a transition to fully-remote operations. Key dates are highlighted in red.

the following day. For MSL, the fully-remote operations concept was proven, but had to be expanded to the entire team. The MSL downlink team was ready, but uplink team still had training, procedures, and setup to complete. MSL tactical uplink stood down for a single planning shift, leaving two days until the next planning cycle because of a pre-scheduled DSN station downtime. That provided sufficient time for not only the MSL operations team at JPL to prepare, but also for the science instrument teams who had to move operations from their institutions to their homes as well. All the preparation and testing culminated in a successful, almost fully-remote, tactical operations shift on March 20. The plan included one of Curiosity's more complex activities, drilling a hole with the robotic arm. Downlink assessment on Monday, March 23, determined that Curiosity had successfully drilled the Edinburgh target.

When the rest of the MSL shifted to fully-remote operations, a single individual ACE initially continued to come on-site to the JPL campus to transmit the command load. This final role transition to working from home completed the transition to fully-remote operations for MSL on April 28, 2020.

Equipment Distribution

The need for multiple simultaneous web conferences meant that some team members would need to literally have one conference room in each ear and swap between them. Additional screen space was key to managing the additional communication tasks in addition to the normal operations duties. The JPL IT catalog and ordering process is not geared towards this specific type of need or the urgent timeline. Approval was obtained for an expedited procurement of headsets, dongles, and red/cyan stereo anaglyph glasses. Additionally, MSL inventoried spare monitors, cables, keyboards, and mice from the previous ground system upgrade and made these items available to MSL personnel for home use. These items were collected in a conference room for team members to sign out on the last on-site operations day, and MSL management coordinated distribution after mandatory telework was instituted.

Team Member Tool Tests from Home

In advance of the aforementioned remote operations thread tests, discussed in more detail later, smaller tests were conducted by several team members to gauge the feasibility of using the full suite of tools required in regular operations through remote connections to the MSL workstations normally used in person at JPL as described in Sections 3-4. Initial tests of the remote desktop VNC appeared to demonstrate that whilst not as responsive or reliable as on-site operations, remote use of MSL workstations in this manner would likely be sufficient for normal operations. Changes from VNC Virtual Mode to Service Mode, detailed in Section 4, were found to enable full 3D hardware accelerated graphics and dramatically improved performance of RSVP as a result. This change is the largest factor enabling successful fully-remote operations of complex RP activities without needing to expend significant project resources to improve RSVP software or deploy new specialty hardware to homes.

The urban surroundings of JPL in which most team members live are fortunately well connected with a variety of domestic cable, ADSL, or fiber internet connections. The FCC defined fixed broadband of 25 Mbps is available to 98.9% of the urban California population and furthermore the FCC reports that 100% have access to mobile 4G speeds of at least 5 Mbps [7].

To ascertain potential bandwidth limitations for remote operations, generic speed tests and usability tests were conducted from team members homes. Team members were asked to confirm their networks connections met the minimum JPL institutional requirements for telework (recommended 20-25Mbps download speed for video conferencing). For some team members, home network speeds did not meet those requirements. However, individual usability tests and later remote operations thread tests revealed that even users with slower network connections were able to successfully participate with audio and screen sharing during the shift.

Individual usability tests were conducted by using both MSLICE and RSVP in conjunction with networking tools to artificially constrain and measure bandwidth. Screen and audio to web conference rooms were run in parallel to assess impacts of the communication infrastructure. Speeds as low as 4 Mbps were found to be sufficient for MSLICE whereas the more intensive RSVP appeared to degrade at speeds below 20 Mbps. These tests suggested that most team members would be able to conduct their work remotely, and even rely upon 4G hotspots as a potential backup for less resource intensive tasks, such as MSLICE and simple command line tools.

End-to-End Testing

An entire planning shift includes the tactical and supratactical processes described in Section 2. Testing for fully-remote operations needed to exercise all facets of an MSL planning shift and verify the results before use for actual rover commanding. This was achieved through testing a complete simulated tactical downlink and uplink cycle. Since the team determined that the communications solutions and tool updates in the tactical uplink process would also meet the supratactical process needs, supratactical was not included in the end-to-end testing.

Downlink process—The first demonstration of fully-remote downlink operations occurred on March 12, 2020, when the team performed a Downlink Remote Operations Thread Test (DROTT). The downlink shift chosen for the test had previously consisted of only on-call support rather than a full spacecraft assessment. The shift was converted to a nominal one-sol downlink assessment of data from sol 2701. By structuring the test this way, the team was able to test the remote work infrastructure using actual rover telemetry and data.

The team was asked to report on various aspects of their ability to carry out all job responsibilities, including the quality of the remote audio, any issues running subsystem-specific tools, and whether any additional time was needed to complete assessing the downlink.

The DROTT successfully demonstrated the downlink team's ability to perform a virtual downlink assessment. Only minor issues were reported with running downlink tools remotely and all roles successfully completed their tasks. These results provided confidence that fully-remote downlink operations could start immediately, if necessary.

Uplink process —Typically, when testing the uplink process, the unit under test is a process improvement, tool update, or both. The Remote Operations Uplink Thread Test (ROUTT) had very different objectives: verify remote tactical communications, RP toolset remote performance, and all roles' remote access performance. The ROUTT developers determined that exercising the tactical planning process just shy of command delivery would be sufficient to determine success. After that point in the tactical uplink process, the tools used are command-line based, and many roles are released to on-call, thus reducing the communication challenges. Test success would need to include collaboration between the RPs and science roles, as well as among the roles typically co-located in the same room. All roles would need to fully participate in planning meetings and communicate their needs.

In order to run many of the tools in the uplink process, they must be seeded with the vehicle state provided by a full downlink assessment. For full data availability, the test must occur on the operations venue versus a less-populated test or training venue. ROUTT used the state from the most recent sol's assessment (sol 2700) and planned a fictitious future sol (sol 2848) for which data could easily be erased once the test was completed. The team created a sol 2848 skeleton plan that would include both contact science and driving, called a touch-and-go sol. This plan content would exercise all of the RP tools, the RP and science team communication interfaces, and the other types of typical science and engineering activities.

The ROUTT plan leveraged upon a previous test performed on the operations venue that was conducted in September of 2019 to support an entire GDS hardware/machine upgrade. This baseline test structure with the confidence of lessons learned proved invaluable to get the ROUTT ready in such a short time, reducing the ROUTT's execution risk.

Early on in the ROUTT, chances for a successful test looked grim. Many team members had issues connecting to the JPL VPN that was struggling due to the concurrent lab-wide telework exercise. An alternate connection approach was identified and shared over the enterprise chat. After that early difficulty, the testers progressed up the learning curve and after a few hours had adjusted well to the juggling of multiple web conference rooms, mute buttons, and chat rooms. The ROUTT successfully completed, taking only 1.2 hours longer than a normal uplink shift to that point. The team built a complicated touch-and-go single-sol plan and all tactical uplink roles successfully participated. One role simulated the need for MSL GDS technical support and joined yet another web conference to troubleshoot via a shared screen. The team even went beyond the test plan and exercised portions of the process after command delivery and addressed how to run the last meeting of the day that typically has two different presenters. There were lessons to carry forward, of course, but no show-stoppers. Next step was to implement on a full scale and train the entire team.

ACE Testing

The critical ACE function required its own testing for remote support due to its unique on-site and firewall dependencies. The ACEs started testing a week after JPL started mandatory telework. The first ACE tests made use of MSL DSN time reserved for anomaly response and did not impact the typical uplink schedule, as they did not send any commands. On April 15, 2020, the testing progressed to a remote ACE radiating flight command bundles from home to the Curiosity rover while a parallel back-up ACE monitored on site. After three successful commanding sessions without issue, the back-up on-site ACE was released on April 28.

6. Feasibility for Long-Term Remote Operations

Impacts of Human Factors on Sustainability

The tactical planning process now depends not just on the infrastructure of JPL and the institutions of remotely participating instrument and science team members, but also on the reliability of power and internet at dozens of team members' homes. Disruptive local events have caused team members to seek out a colleague to substitute in for part or all of a tactical shift. These events range from minor internet outages to destructive California forest fires. This unavoidable increase in infrastructure fragility continues to present a risk to the reliability of mission operations, but has yet to be realized as a significant change to any planned activities.

As the role is considered one of the most technically challenging, the sustainability of remote operations for the RPs has been studied especially closely. Brief surveys were conducted of the RP team four and six months after beginning remote operations (n=10 and 20 respectively). Asked to rate the quality of their work and performance as a tactical RP, 45% of respondents described their performance as "good" after four months, but this number increased to 70% after six months. Asked to rate their stress level as low, medium, or high – 70% responded as "medium" at four months with the remaining 30% responding as low. These number improved to only 20% reporting medium stress and the remaining 80% describing their stress as low at the six-month mark. Overwhelmingly, in both surveys, respondents said they would be willing to work remotely indefinitely.

Mission Performance and Productivity

As discussed in Section 4, MSL's transition to fully-remote operations did require an adjustment to the number and/or complexity of science activities that could be developed and executed in a given planning cycle. Despite this reduction, the pace of operations (average number of shifts per month) remained at on-site operation levels allowing the project to continue meeting the science objectives for Curiosity's current location in Gale Crater, a clay-bearing geologic unit.

As of October 1, 2020, the team has completed 4 drilling campaigns (Edinburgh, Glasgow, Mary Anning and Mary Anning 3), and analyzed the samples in its two onboard laboratories. These included two wet chemistry experiments using Curiosity's Sample Analysis at Mars (SAM) instrument [8]. These particular experiments are designed to look for past and present habitability of Mars by exploring molecular and elemental chemistry relevant to life. They use chemical solvents (hence "wet" chemistry) that Curiosity carried to Mars in nine sealed cups. If organic molecules in the drilled rock samples are combined with these chemicals (meaning they are "derivatized") before they are heated by SAM, they are more likely to be detected. Given that wet chemistry experiments are some of the most complex on-board the rover and make use of precious consumables, the instrument team typically performs dry runs on a high-fidelity testbed at NASA's Goddard Space Flight Center before executing on Mars. However, COVID-19 related challenges meant that the testbed was not available and the team needed to perform the dry runs on Curiosity itself, an adjustment that the JPL and instrument team made successfully. In addition to multiple drilling campaigns, the rover continued its traverse through the clay-bearing unit traveling 1,160 meters towards the next major geological region – a sulfate bearing unit higher on Mount Sharp.

Challenging engineering operations have continued remotely including the uplink of a minor flight software update to enhance the redundant Rover Compute Element's ability to act as a lifeboat in the event of any future hardware issues. Development and testing of a major flight software update is ongoing. Most of this work is being conducted remotely with a minimum engineering team conducting on-site testing using a nearly identical clone of Curiosity known as the Vehicle System Test Bed (VSTB). The operations team has also successfully addressed several anomalies during fully-remote operations without any need to adjust anomaly disposition and resolution procedures.

On-site operations requires not only that an engineer be experienced with their subsystem and the procedures and tools used to operate it, but also be familiar with the other roles on shift, have a level of sympathy to colleagues' workloads and an understanding of how and when to communicate with those other roles for needed coordination. Early in fully-remote operations it became clear that a major challenge would be "attention spread" – trying to manage those multiple lines of communication. These challenges have been realized as delays in the tactical timeline resulting in a moderate increase in shift duration when compared to shifts of similar complexity conducted in person on-site.

When remote operations first began there were concerns that these challenges could result in an additional two hours added to the average seven hours required for a tactical planning shift. After a few weeks, the average time for a tactical shift returned to little more than the average seven hours of on-site operations.

Training of New Personnel

Any operations team like that of MSL has a flux of personnel over time as team members leave for new projects and are replaced by new team members. Shortly after beginning remote operations, it became clear that maintaining that onboarding process and training new team members in operations roles would need to be continued remotely. Apprentice style on-shift training, referred to as shadow shifts, for all roles in tactical operations was initially put on hold. Tactical shadow shifts started again on March 25, 2020 with the Engineering Camera Payload Uplink Lead role (ECAM PUL). The new trainee in question had started shadow shifts on-site earlier in the year. TUL and SP trainees who started their training during on-site operations resumed shadow shifts shortly thereafter. That was followed by the first trainee completely new to MSL, an ECAM PUL trainee, in June 2020. This trainee successfully completed their training at the end of September. Existing RP trainees also resumed shadow shifts in June, with new trainees beginning in August.

The TUL role initially only continued training of two advanced trainees, both of whom completed certification under fully-remote operations. A new TUL trainee (an individual already experienced in other MSL operations roles) is expected to begin their first shadow shift in October, 2020. On-site practices used for trainer-trainee interactions included direct in-person communication when possible, but relied heavily on chat for private communication and communication during meetings to avoid disruptions of other on-site team members. To avoid additional attention spread, training communication now occurs almost entirely within chat and occasionally makes use of the tactical web conference audio channel.

During ECAM PUL training in April 2020, attention spread described earlier was being inadvertently worsened by the added ongoing phone-call between the trainer and trainee. This resulted in a benign commanding error in the form of a series of specifically targeted photometry observations being wrongly pointed, thus necessitating reacquisition with correct pointing on a subsequent sol. The scientist making the request had described the required pointing in one of the chat rooms, but neither the trainee nor trainer saw it before delivering the sequence. Refinements have since been made to procedures and enhanced training given to both the ECAM PUL team and science team members to ensure that the receipt of specific requests are acknowledged by the implementing PUL.

Whilst maintaining a well-trained team continues to be a challenge, the majority of the tactical roles involved in mission operations have successfully begun training new team members remotely. For the SP, RP, EUL, and TUL roles the use of remote simulated tactical shifts informally known as Practical Operational Readiness Gambits ("PORGs") has enhanced the training cadence of those roles [9].

Returning to In-Person Operations

As of this writing, JPL policy permits only personnel whose tasks require a physical presence, such as direct interaction with hardware, to be on site. As the pandemic recedes, we can foresee a return of MSL operations team personnel to the JPL facility (and MSL science team members to their home institutions), with many team members again co-located in the JPL MSL operations facilities.

It is not clear at this point whether such a transition will represent a return to pre-pandemic "normal" conditions. There may be a transient loss of operational efficiency as some communications pathways among roles are altered and team members in some roles train or retrain to perform their roles in person. Some personnel have joined MSL since the start of forced telework, and have never performed their roles co-located with others.

While fully-remote mission operations has presented the many challenges described in this paper, it has also reduced the demand on previously over-subscribed JPL resources, such as parking capacity and office space. Continued telework of a large segment of the JPL workforce might be encouraged, resulting in a hybrid strategy with some individuals – or operations roles – continuing to work remotely on many of their workdays for the foreseeable future.

Certain aspects of the updated toolsets and procedures developed for fully-remote operations will likely continue to benefit the team during on-site operations. The use of the virtual supratactical whiteboard provides several efficiency improvements over the physical implementation it replaced. The widespread use of VNC by the team will in all likelihood persist in a return to on-site due to the hurdles and inconveniences related to physical machine access.

The experience gained by MSL has been shared with other missions conducting and preparing for operations at JPL. The Mars 2020 mission conducted its first operational readiness test in the fall of 2020 with some personnel supporting remotely and some on-site. A number of procedures and practices were adopted from MSL including the use of multiple web conferencing rooms as well as usage of VNC. Mars 2020 continues to develop its remote operations strategy including remote usage and monitoring of on-site testbed resources. It is anticipated that some portion of Mars 2020 surface operations starting in February 2021 will be conducted remotely.

7. SUMMARY

Several members of the MSL operations team working from home are shown in Figure 6. The most remarkable aspect of MSL's transition to fully-remote operations has been the juxtaposition of many team members' strong initial doubts of its feasibility and those same individuals now remarking on how little has actually changed over the course of the transition. Every planning day still starts and ends working alongside our colleagues who maintain their commitment to the mission's goals of exploration and discovery. While we may no longer be sitting next to one another physically in an operations room, we still remain steadfast stewards of Curiosity and continue to address all the unique challenges associated with a planetary surface exploration mission. Our team has taken the additional connectivity and communication challenges in stride as we eagerly await the next downlink, so that we may begin planning the Curiosity rover's activities on the following sol from our home offices, kitchen tables, and couches.

Figure 6. MSL operations team members working from home.

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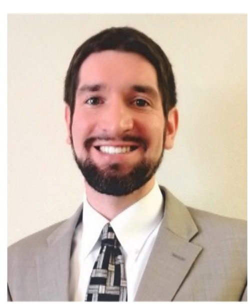
Biography

Matthew Gildner *is a Mars Science Laboratory Rover Planner, a former RP role lead, and a robotics researcher at JPL. His research focus is in the area of field robotic systems for planetary surface sampling as well as commercial robotic servicing and inspection. Matthew completed his M.S. degree in Mechanical and Ocean Engineering in 2012 at the Massachusetts Institute of Technology.*

Alicia Allbaugh*. received a B.S. in Engineering Physics in 1988 from the Ohio State University and a Ph.D. in Physics from the Kanas State University in 2003. She has been at JPL a combination of 22 years starting her career on the Galileo mission. She joined MSL in 2006 and is the Integrated Planning and Execution Team Chief. She currently also supports Mars Sample Return operations development.*

Andrew Mishkin *is the Mission Manager for the Mars Science Laboratory mission. During his time at JPL he has served as a systems engineer on tasks related to autonomous rover navigation and human spaceflight. He led the mission operations design and development for the Sojourner, Spirit, and Opportunity Mars rovers. He holds B.S. and M.S. degrees in Systems Engineering from the University of California, Los Angeles.*

Stirling Algermissen *received a B.S. in Computer Science from Boston University in 2012. He is a Mars Science Laboratory Rover Planner certified for mobility, arm, and sampling operations. He has also participated in MSL operations as a OPGS shift lead and tactical analyst, Engineering Camera Payload Uplink and Downlink Lead, and as a Payload Downlink Coordinator. Beyond MSL, he serves as the SWOT Processing Control and Data Management Subsystem Lead. And the M2020 Instrument Data System Subsystem Lead.*



Matthew Van Kirk *is the Engineering Operations Team Chief for the Mars Science Laboratory mission at JPL. Since the start of his career in 2008, Matthew has had the privilege of operating each of the Spirit, Opportunity, and Curiosity rovers on Mars. Matthew earned an M.S. degree in Aerospace Engineering from the University of Michigan.*

Doug Ellison *received a B.S. in Multimedia Design from De Montfort University in Leicester, England in 2001. He joined JPL in 2010 to work on data visualization projects for education and public outreach before joining the Mars Science Laboratory team in 2016 as part of the Engineering Camera Payload Uplink team. He became the Engineering Camera Team Lead in 2019*

Dr. Carrie Bridge *received a B.S. in Physics and Geophysics, followed by a Ph.D. in Astrophysics from the University of Toronto, Canada. She is the Science Operations Team Chief for the Mars Science Laboratory mission and the Group Supervisor for Science Planning at JPL. Prior to joining JPL she was a Staff Scientist at Caltech where she led multiple international projects studying galaxy formation and evolution utilizing NASA's Hubble, Spitzer, WISE and Herschel Space Telescopes, as well as ground-based facilities such as Keck.*

Tim Stough *received a B.S. in Electrical and Computer Engineering from Purdue University in 1995 and a M.S. in Electrical Engineering with a concentration in Machine Learning in 1997. He joined JPL in 1997 to work on data mining and machine learning. He has worked in data system architecture, science applications, and science application program management before joining the Mars Science Laboratory team in 2017 as part of the Science Planner and Sequence Integration Engineer team. He became the SPaSIE Team Lead in 2019.*

Ashley Stroupe *Stroupe is a JPL Spacecraft Operations Engineer. She has a B.S. in Physics from Harvey Mudd College, an M.S. in Electrical Engineering from George Mason University, and a Ph.D. in Robotics from Carnegie Mellon University. She joined JPL as a robotics researcher in 2003, and began rover operations with the MER project in 2004. Presently, she is the role lead for the MSL Rover Planner role and deputy role lead for the Tactical Uplink Lead role.*